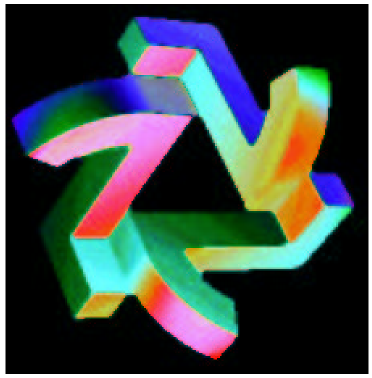
Neutrinos



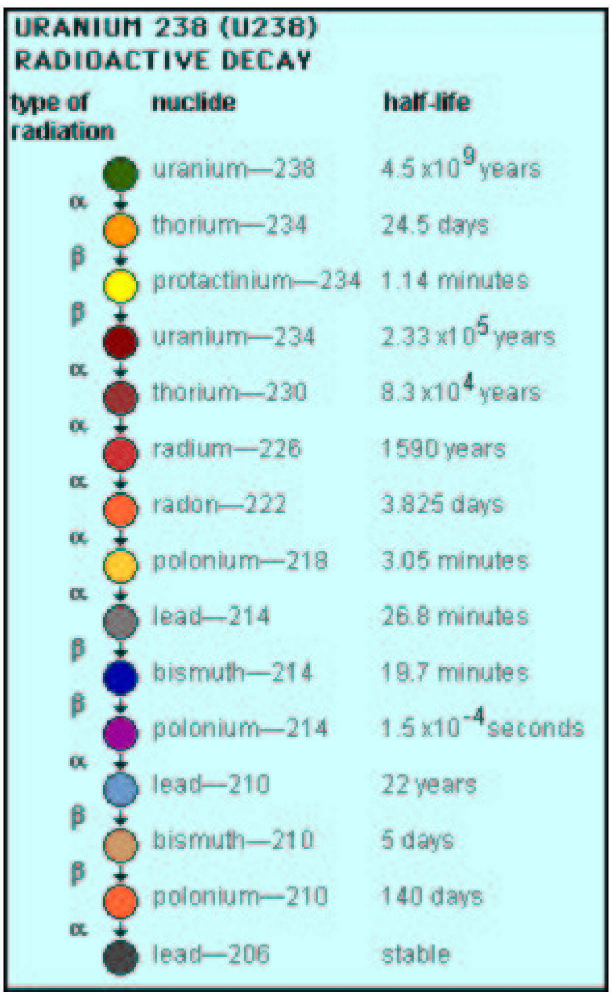
Milind Diwan, Brookhaven National Laboratory
631-344-3327

July 30, 2002

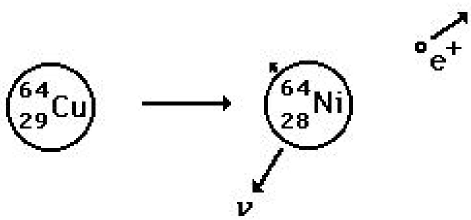
- What are neutrinos ?
- Why study them ?
- What are the properties ?
- What are they good for ?
- Some history
- Natural sources
- Man-made sources
- The latest story

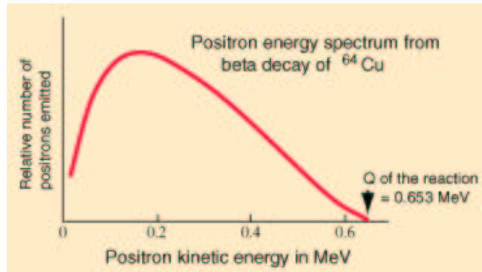
What are neutrinos ?

- Neutrinos (ν) are electrically neutral, (almost) massless particles emitted in decays of radioactive nuclei (beta decays).
- Every emission of a Beta particle is accompanied by a neutrino !



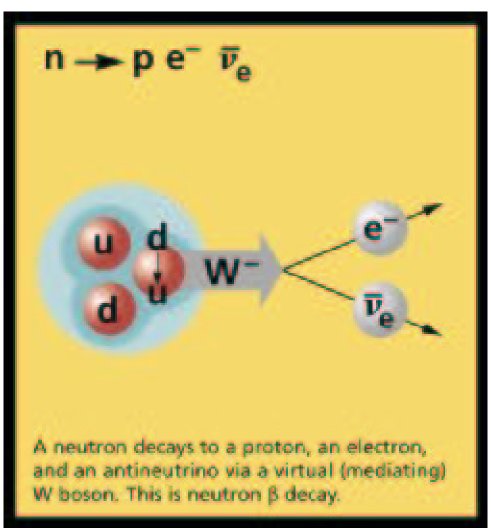
Pauli and his letter





In 1930 W. Pauli proposed the Neutrino because the observed beta decay energy spectrum appeared to violate energy conservation.

At that time proton, electron, and photon (light) were the only known elementary particles. Pauli named it Neutron initially; it was later named Neutrino by Fermi.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

Pauli's letter

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that my remedy could seem incredible because one should have seen these neutrons much earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think about this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant, W. Pauli

Why study neutrinos ?

- Essential part of the building blocks of matter and the Universe.
- They cause or are a consequence of extraordinary and deep principles of nature.

Standard Model of Particle Physics

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	−1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	−1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	−1

Quarks spin = 1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	−1/3
c	charm	1.3	2/3
s	strange	0.1	−1/3
t	top	175	2/3
b	bottom	4.3	−1/3

What are their properties ?

- Nearly massless.
  New evidence that they have tiny masses !
- No electric charge. Their interactions are WEAK.
- They are paired with other charged particles called LEPTONS (electron, muons and tau)
- They spin only counter-clockwise as they fly ! (anti-neutrinos spin clockwise as they fly)
- When they interact they only produce the lepton they are engaged to !

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	25	Not applicable to quarks
Strength for two u quarks at: 3×10^{-17} m	10^{-41}	60	
for two protons in nucleus	10^{-36}	Not applicable to hadrons	20

Property \ Interaction	Weak (Electroweak)	Electromagnetic (Electroweak)
Acts on:	Flavor	Electric Charge
Particles experiencing:	Quarks, Leptons	Electrically charged
Particles mediating:	W^+ W^- Z^0	γ
Strength relative to electromag for two u quarks at: 10^{-18} m	0.8	1
Strength for two u quarks at: 3×10^{-17} m	10^{-4}	1
for two protons in nucleus	10^{-7}	1

What are they good for ?

- They puzzle us ! One learns by solving puzzles.
- Do they have mass ?
- If they have mass what implications to left-right properties ?
- Why is the mass so small ?
- Can they turn into each other ?
- How many of them are there in the Universe ?
- How do they interact with quarks ? Do we know enough ?

Tutorial on Neutrino events: 1

- $N_{events} = Flux \times Cross - section \times Targets$
- Flux: F has units of per area per unit time. e.g. $10^{13}/cm^2/sec$
- Cross section: σ has units of area e.g. $10^{-38}cm^2$
- Targets: the number of targets in the detector 1 ton of water $\sim 6 \times 10^{29}$ protons and neutrons.

$$N_{ev} = F \times \sigma \times N_{targets} \times \epsilon$$

Practical experiments have efficiency, ϵ.

The numbers are functions of neutrino energy.

Energy is measured in electron-volts.

1 eV: $1.6 \times 10^{-19}J$.

MeV: $10^6 eV$
GeV: $10^9 eV$

Tutorial on Neutrino events: 2

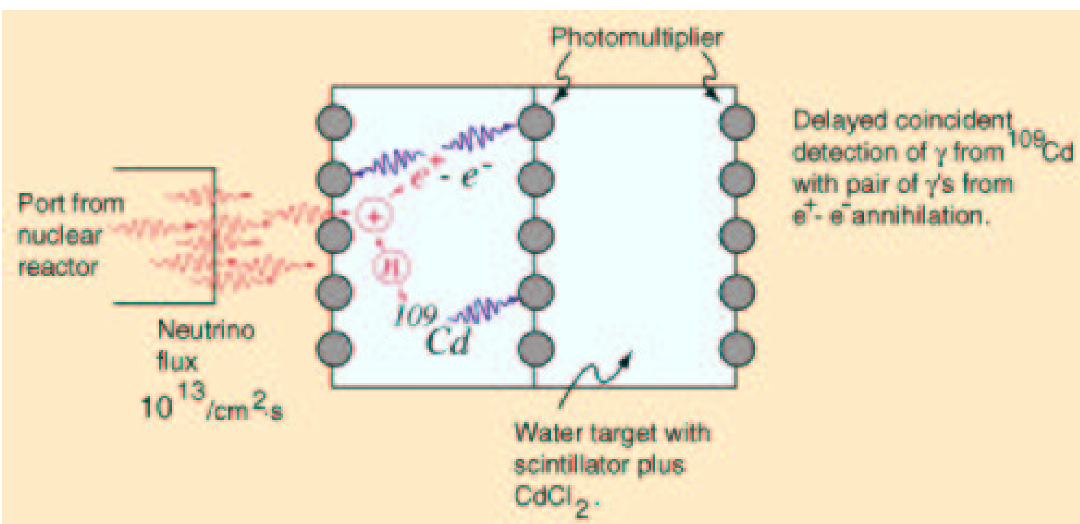
- Energy and Flux of neutrinos from various sources.
  - The SUN ! below 0.5 MeV $10^{11} cm^{-2}s^{-1}$ at $\sim$ 3-14 MeV $3 \times 10^{6} cm^{-2}s^{-1}$
  - Cosmic rays hitting the atmosphere at 1 GeV $\sim 5000 m^{-2}s^{-1}$
  - From radioactive decays in the Earth $10^{6} - 10^{7} cm^{-2}s^{-1} < 3$ MeV from U/Th decays.
  - SuperNova neutrinos. 11 were seen in 1987 in two large detectors.
  - Microwave background neutrinos. Very cold 2.7^{o} ! $300 cm^{-3}$ Multiply by velocity to get flux.
  - Nuclear reactors. $10^{13} - 10^{15} cm^{-2}s^{-1}$ $\leq$5 MeV. Falls as $1/r^{2}$ with distance from reactor.
  - Accelerators. $10^{10} - 10^{11}$ at 1-10 GeV at 100 meters. Falls as $1/r^{2}$ from target.

- Cross section of neutrinos on various targets are small. Detectors must be very large to see enough events.
  - at $\sim 1 MeV$ on protons, neutrons, deuteron
    $\sim 10^{-44} cm^2$
  - at $\sim 10 MeV$ on Clorine, Carbon, etc.
    $\sim 10^{-42} - 10^{-41} cm^2$
  - high energies (1 GeV) on protons and neutrons
    $\sim 10^{-38} \times (E_\nu / GeV) cm^2$
  - high energies (GeV) on electrons
    $\sim 10^{-41} \times (E_\nu / GeV) cm^2$
- Types of reactions
  - Charged current.
    $\nu + N \rightarrow X + L$, L is associated charged lepton
  - Neutral current
    $\nu + N \rightarrow X + \nu$

Reines and Cowan experiment

Pauli bet a case of champagne that nobody would ever detect a neutrino. In 1956, Clyde Cowan and Fred Reines detected antineutrinos emitted from a nuclear reactor at Savannah River in South Carolina, USA. Pauli kept his promise.

"Detection of the Free Neutrino: A Confirmation", C.L. Cowan, Jr., F. Reines, F.B. Harrison, H.W. Kruse and A.D. McGuire, Science 124, 103 (1956).



Reines and Cowan experiment. Result

$\bar{\nu}_e + p \rightarrow n + e^+$, wait few μs, $n + \ ^{108}Cd \rightarrow \ ^{109}Cd + \gamma$

Detect e^+ and γ in sequence to reduce background.

There was 200 kg of water. 1.3×10^{28} free protons.

Detector was placed 11 m from the reactor and 12 m deep.

Observed ~ 3 events per hour.

Confirmed by turning the reactor off.

$$10^{13} cm^{-2} s^{-1} \times 3600 s \times 6 \times 10^{-44} cm^2 \times 1.3 \times 10^{28} protons \times \sim 0.1$$

Nobel prize for Reines in 1995.

Maurice Goldhaber's experiment

M. Goldhaber, L. Grodzins, A.W. Sunyar (Brookhaven). 1958. Published in Phys.Rev.109:1015-1017,1958

Measure the helicity (or spinning direction) of the neutrino !

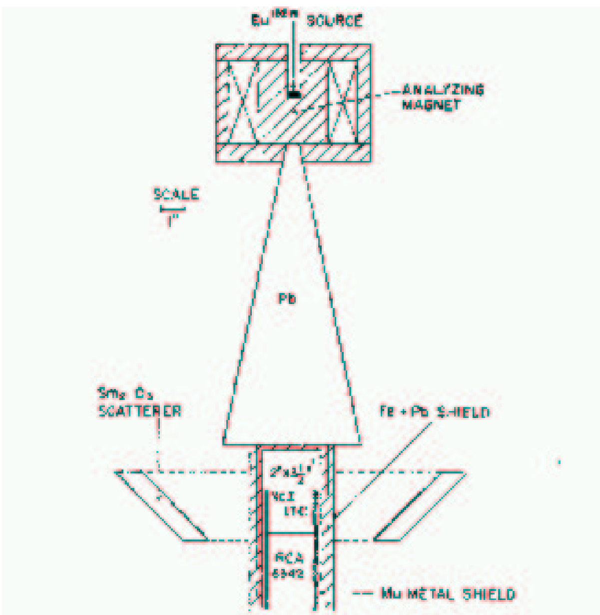


Fig. 1. Experimental arrangement for analyzing circular polarization of resonant scattered γ-rays. Weight of Sm_2O_3 scatterer: 1850 grams.

$$ {}^{152}_{63}Eu + e^-(orbit) \rightarrow {}^{153}_{62}Sm^* + \nu_e $$

$$ {}^{153}_{62}Sm^* \rightarrow {}^{153}_{62}Sm + \gamma $$

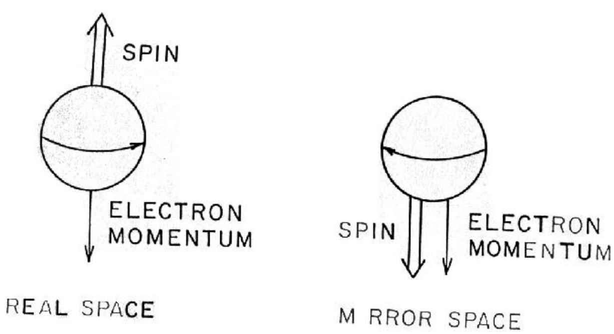
Maurice Goldhaber's experiment

Gamma ray must have same helicity as neutrino. Use magnet to analyse. Reverse magnetic field to observe:

$$\frac{N_- - N_+}{2(N_- + N_+)} = 0.017 \pm 0.003$$

More negative helicity gamma rays than positive

The neutrino you see in the mirror CANNOT exist !



Lederman, Schwartz, Steinberger

Observation of two kinds of neutrinos
Phys.Rev.Lett.9:36-44,1962

Made high energy neutrinos using a proton accelerator.

$p + Be \rightarrow \pi + X;\ \pi^{\pm} \rightarrow \mu^{\pm} + \nu$

Found 34 events that looked like muons (long tracks) instead of electrons (showers).

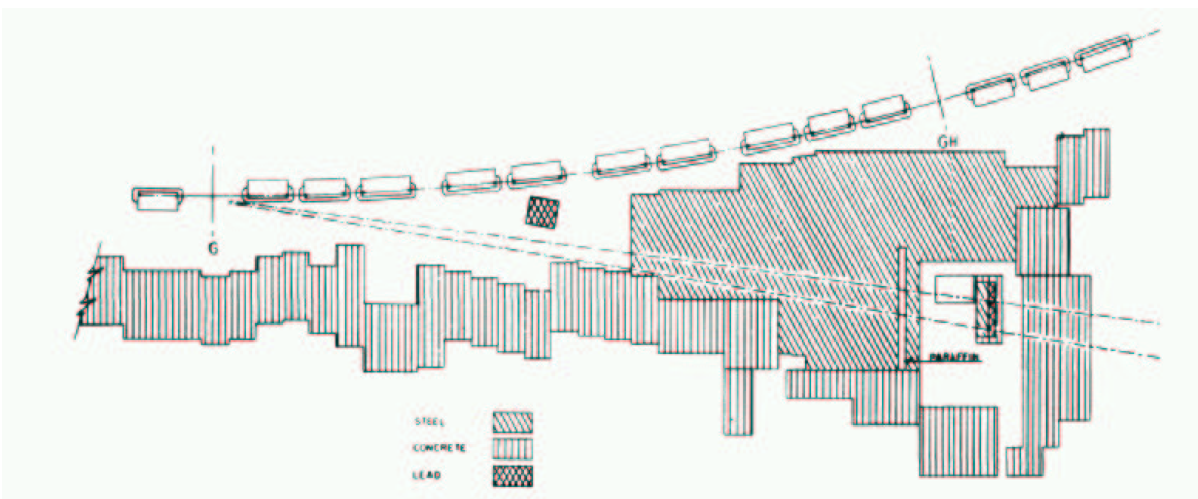


FIG. 1. Plan view of AGS neutrino experiment.

37

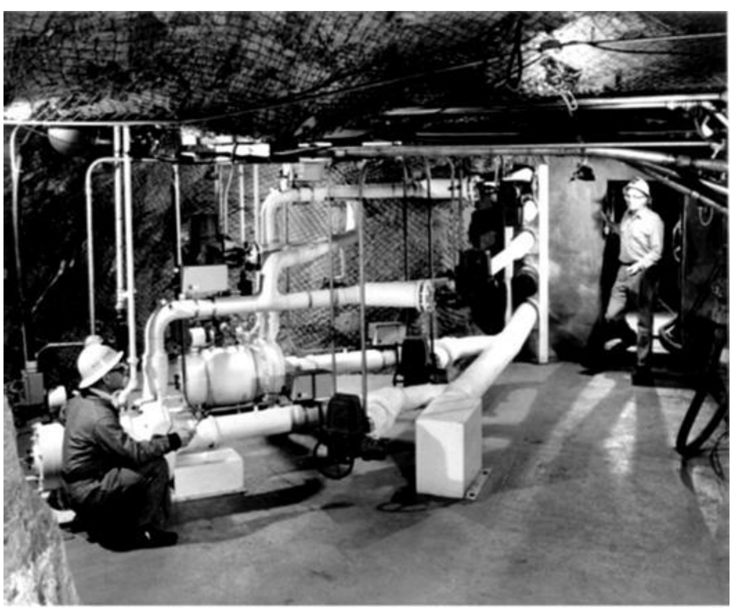
Are all neutrinos the same ? νs produced in association with muons are not the same as νs produced in association with electrons ! Muon type neutrinos make muons when they interact.

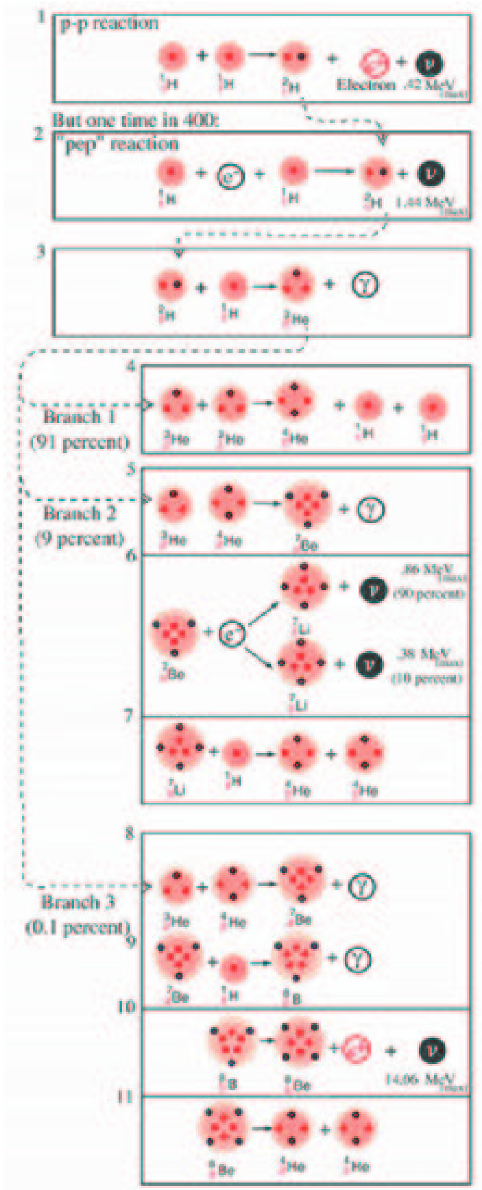
Ray Davis and the gold mine !

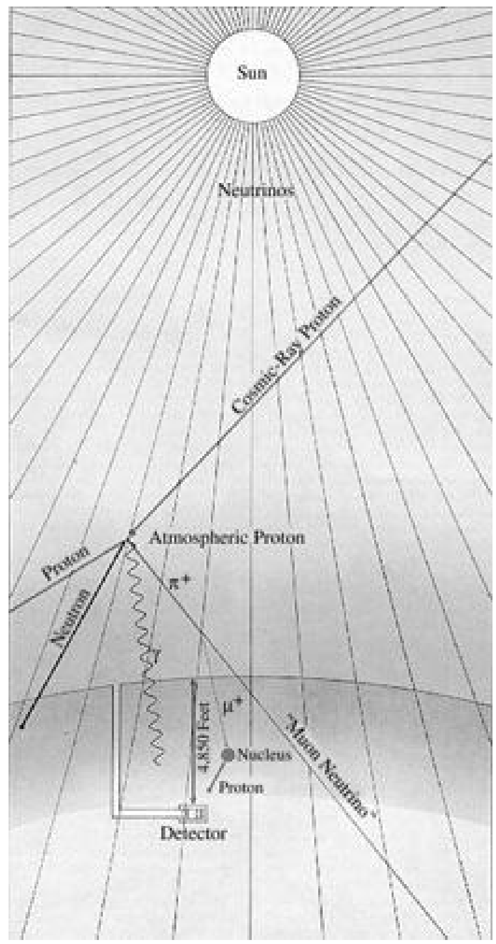
Look at John Bahcall's WEB page to get the full story http://www.sns.ias.edu/ jnb

In 1962, Ray Davis set out to detect neutrinos from the Sun. Large flux but extremely low energy and cross section. Low event rate; high potential background.

Located experiment in a rock cavity 4,850 feet below the surface in the Homestake Gold Mine in the town of Lead, S.D.



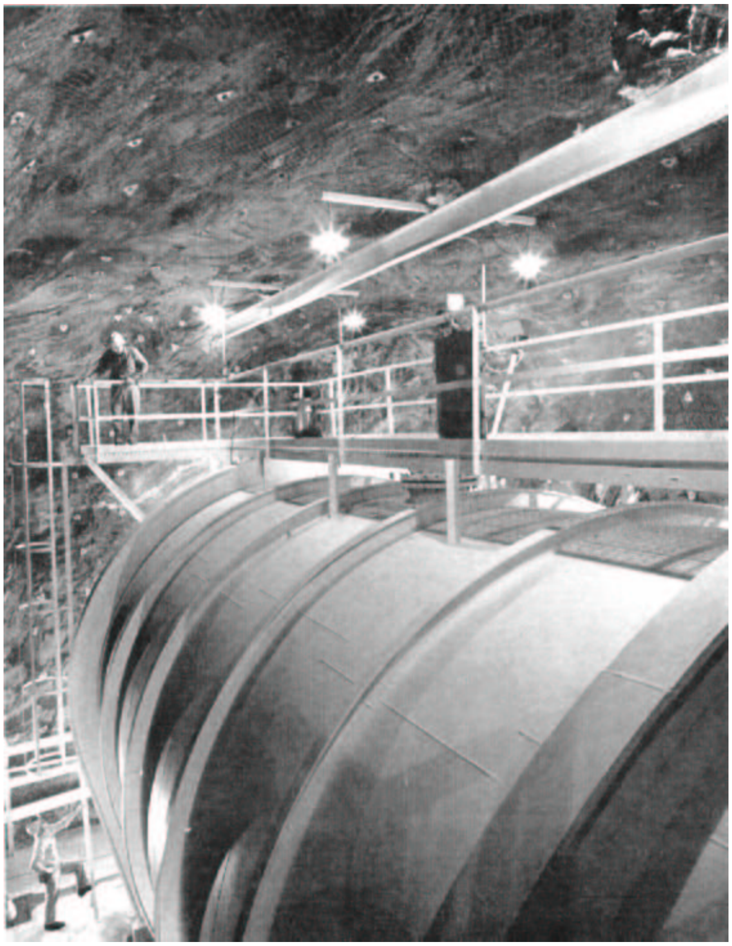




Use 100,000-gallon tank of C_2Cl_4.

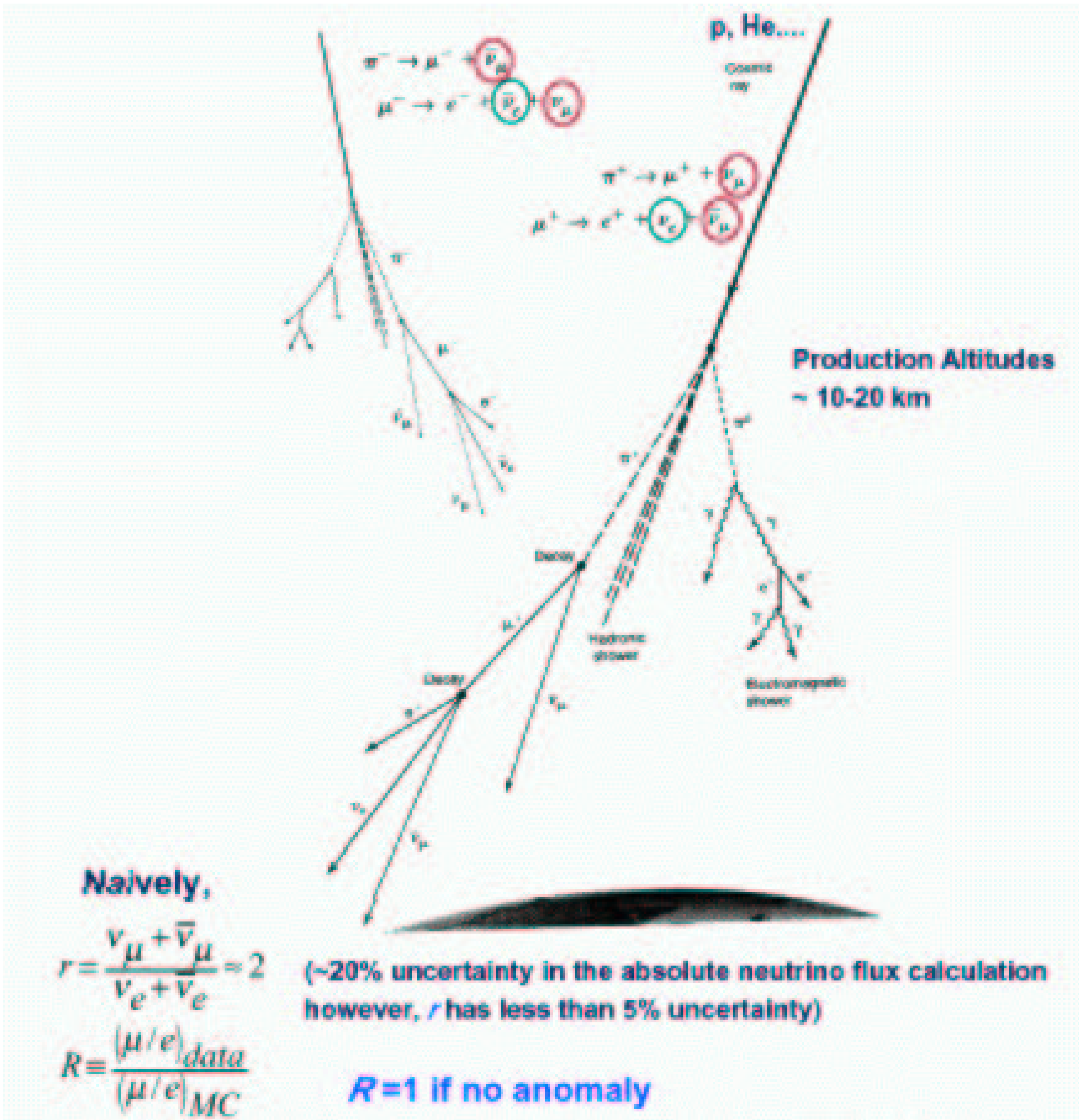
$\nu_e + \ ^{37}Cl \rightarrow \ ^{37}Ar + e^-$

Collect the radioactive Argon atoms ($\tau_{1/2} = 35 days$) and count them in a special apparatus. Count a few atom per day !



Result: Too few counts ($\sim$3SNU) by half compared to the prediction $\sim$6SNU. Where do half of the solar ELECTRON type neutrinos go ?.

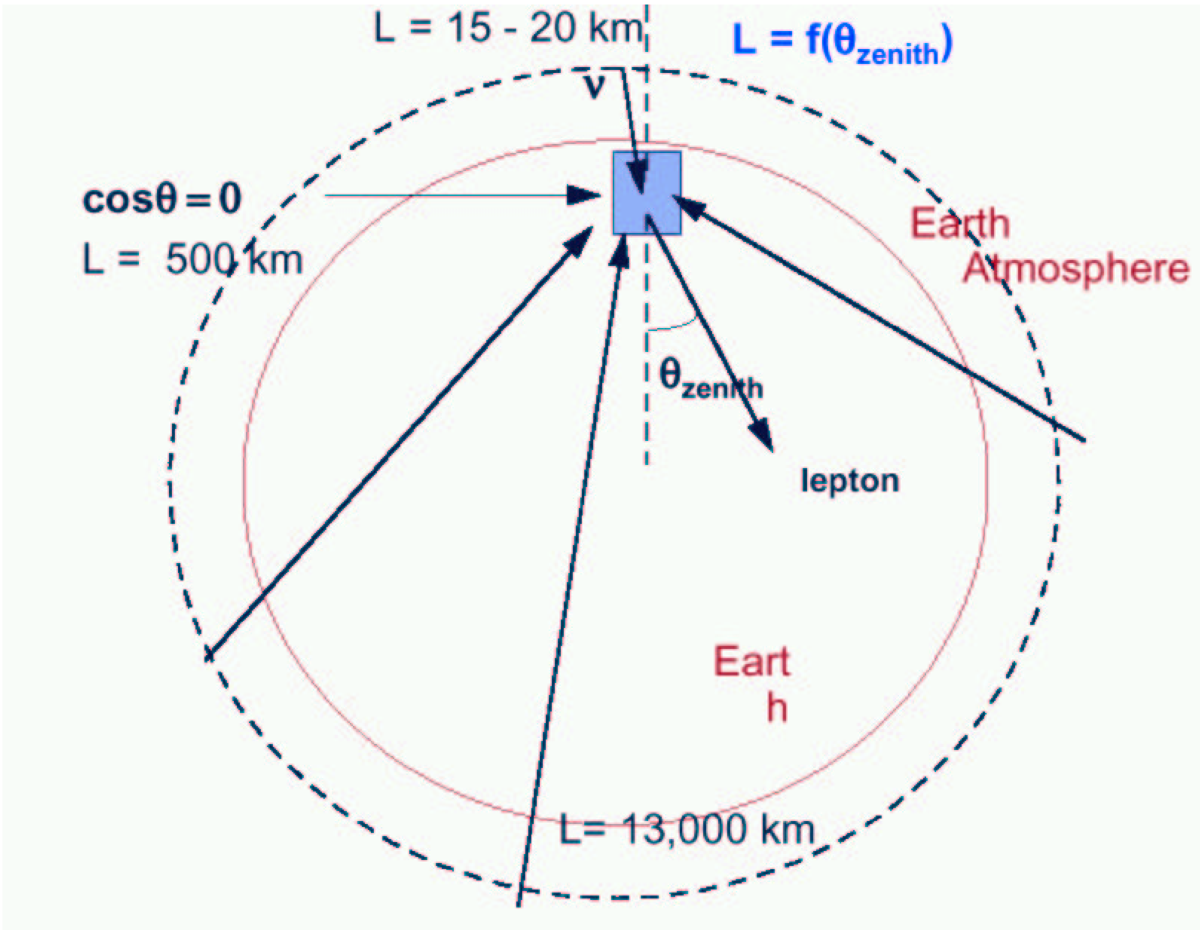
Neutrinos from the Atmosphere



Flux: 5000 $m^{-2}s^{-1}$ at 1 GeV

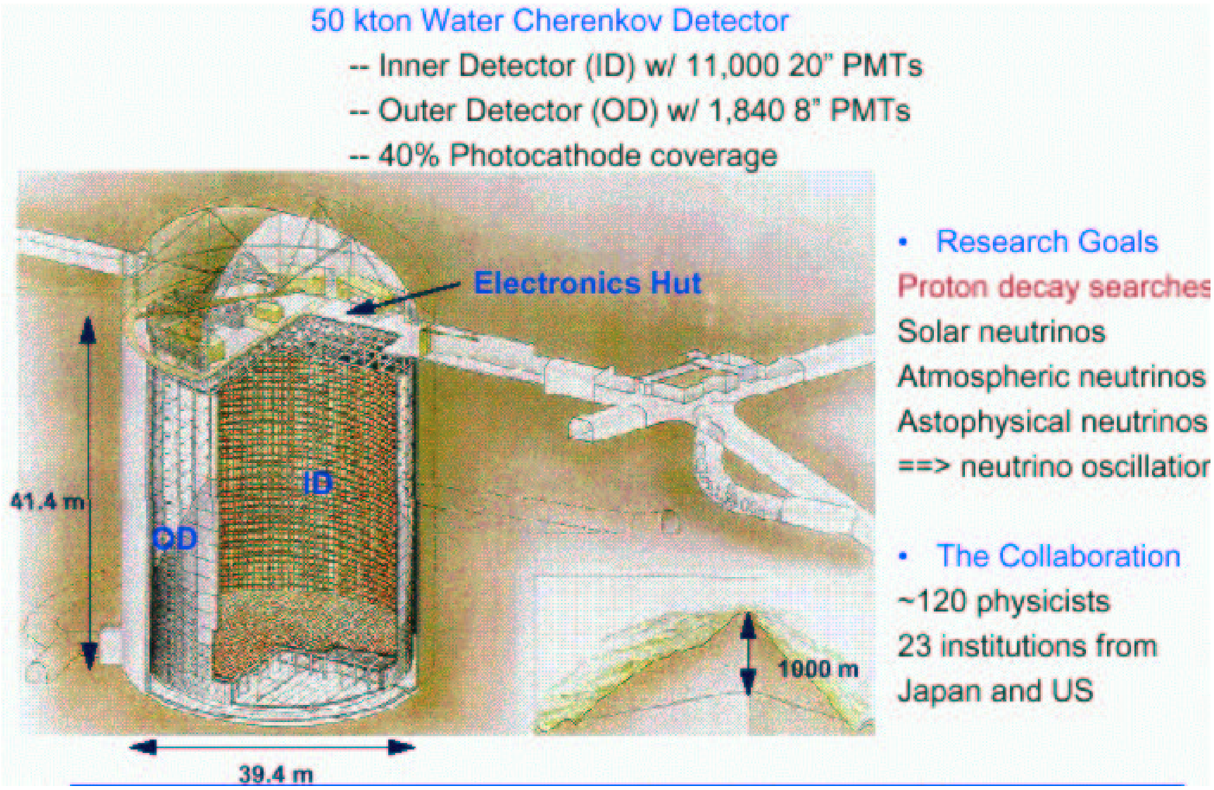
Atmospheric neutrino experiment

Gauss : Same flux from all directions inside a shell.



Experiment located in a copper mine in western Japan.

Super Kamiokande

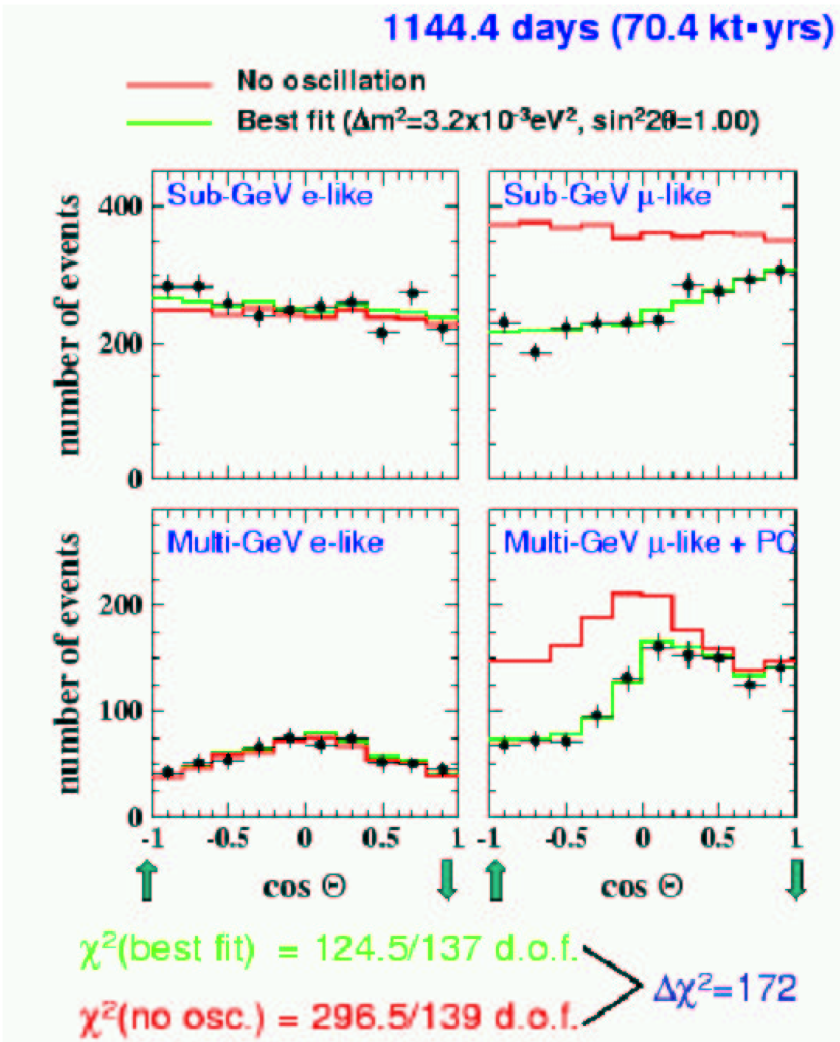


Principles of operation:

Neutrinos react and make charged particles.

When charged particles travel with velocity greater than 1/n (n: index of refraction) they make light which can be detected in photo-multipliers.

Super Kamiokande Result



What is happening to the MUON type neutrinos coming from the other side of the earth ?

The real neutrino story

New picture of neutrinos is emerging.

All three types of neutrinos (Electron, Muon, and Tau) have a tiny mass.

The neutrinos are always in a mixed state of being.

Like a pendulum they swing their identities back and forth while in flight (Neutrino Oscillations).

Therefore, Electron type neutrinos from the Sun turn into other types on their way to earth.

Muons type atmospheric neutrinos generated in the other side of the earth turn into Tau type on their way up.

Paradox: how can you have mass and yet have permanent helicity ?

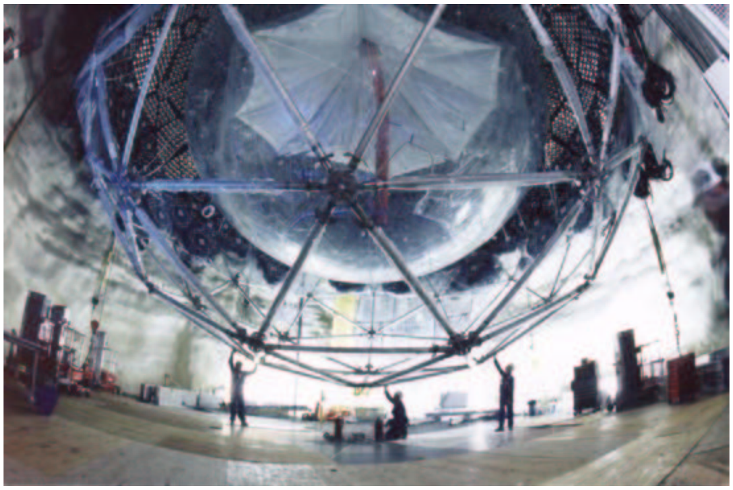
Since a neutrino is massive it travels less than speed of light. If I overtake it, it will appear to change its helicity !

solution: they may be their own anti-particles

Sudbury neutrino observatory

Back to the disappearing Solar neutrinos.

Sudbury Neutrino Observatory. 1000 tons of heavy water D_2O. 11000 photo-multipliers. Very very deep to reduce background in a Nickel mine in Sudbury Canada.



Observe

a. $\nu_e + d \rightarrow p + p + e^-$

b. $\nu + d \rightarrow p + n + \nu$

Reaction (b) is called Neutral Current. It does not depend on the flavor of the neutrino.

Count the total number of neutrinos using (b) and count ELECTRON type neutrinos using (a).

Result: only about 1/3 of the total number of neutrinos reaching earth fro the Sun are ELECTRON type. Phys.Rev.Lett.89:011301,2002

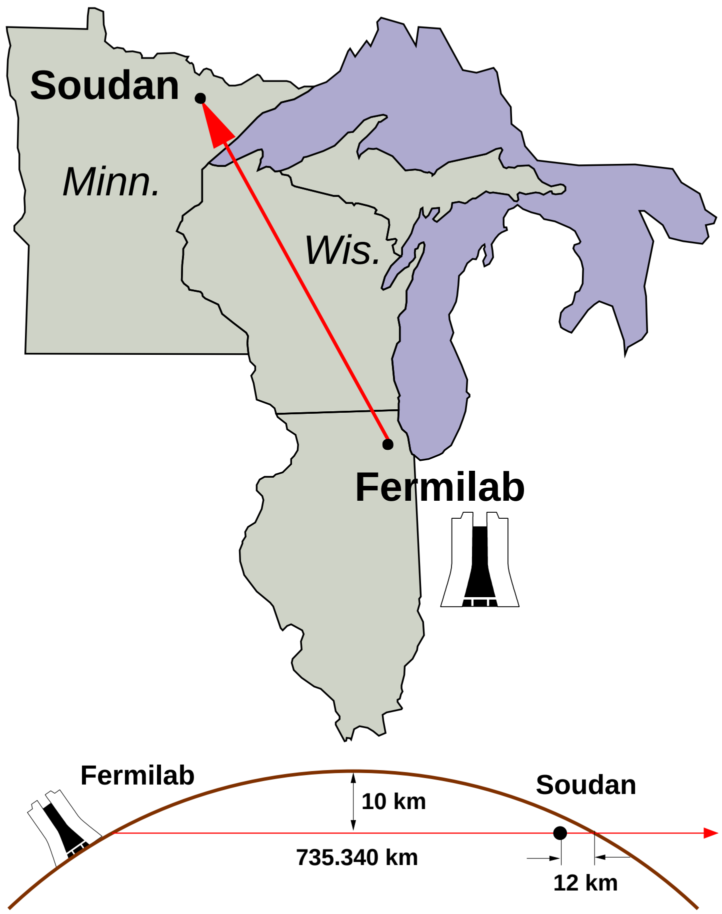
What is Next ?

- Measure the neutrino parameters better
  - Confirmation of the 3 neutrino model needs massive new facilities.
  - Masses: so small that almost impossible to measure unless lucky.
  - Mass differences can be measured extremely well. There are 2 mass differences for 3 neutrinos.
  - 4 parameters govern the “mixing” of 3 neutrinos. At the moment 2 are known somewhat.
- Measure of the neutrinos as own anti-particles. Can only be done by a special decay of radioactive nuclei, called double-beta-decay.

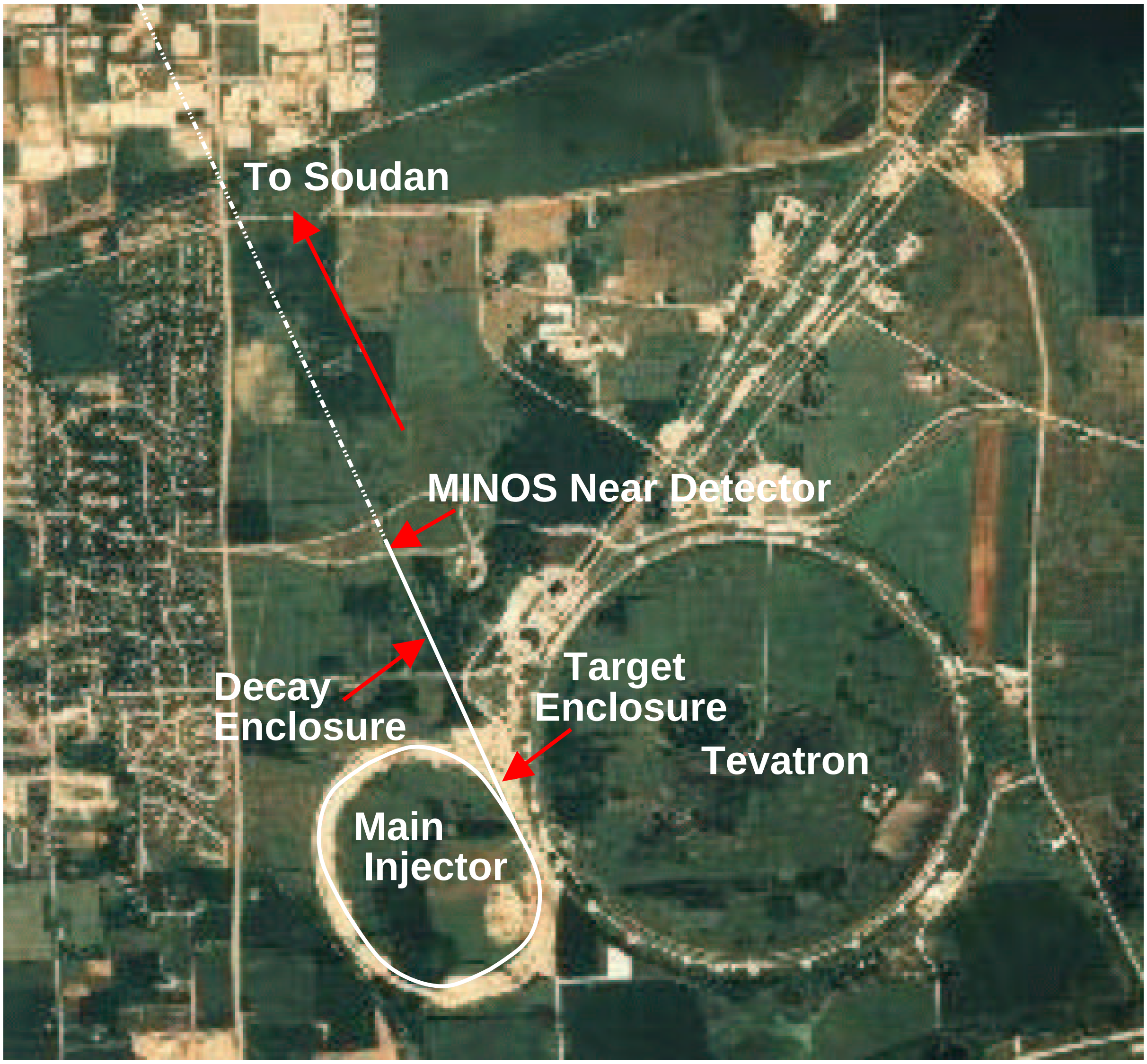
  $N \rightarrow N' + \beta + \beta$

MINOS experiment at FNAL: 1

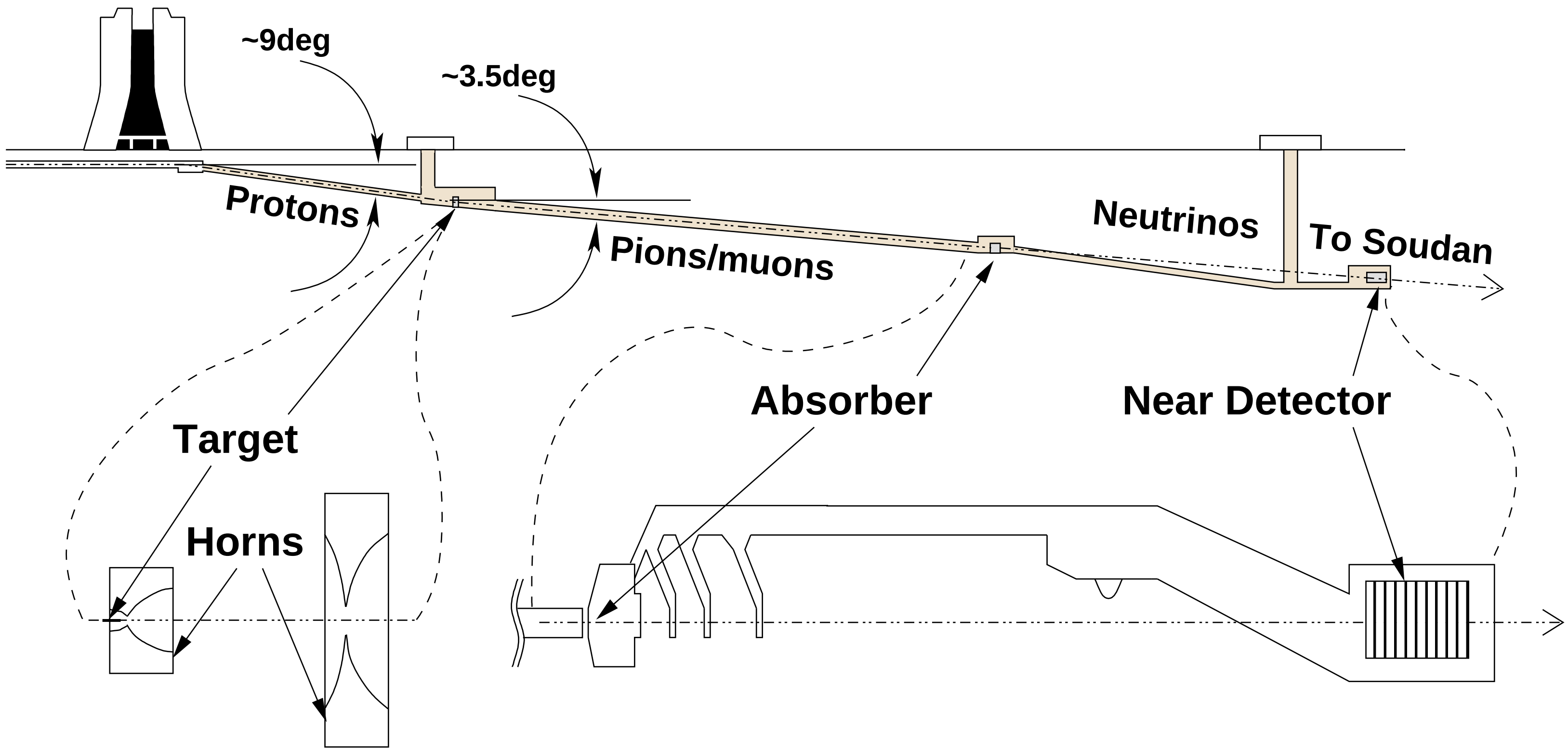
Send an accelerator produced muon neutrino beam a very long distance to confirm the Super Kamiokande observation.



Aerial View

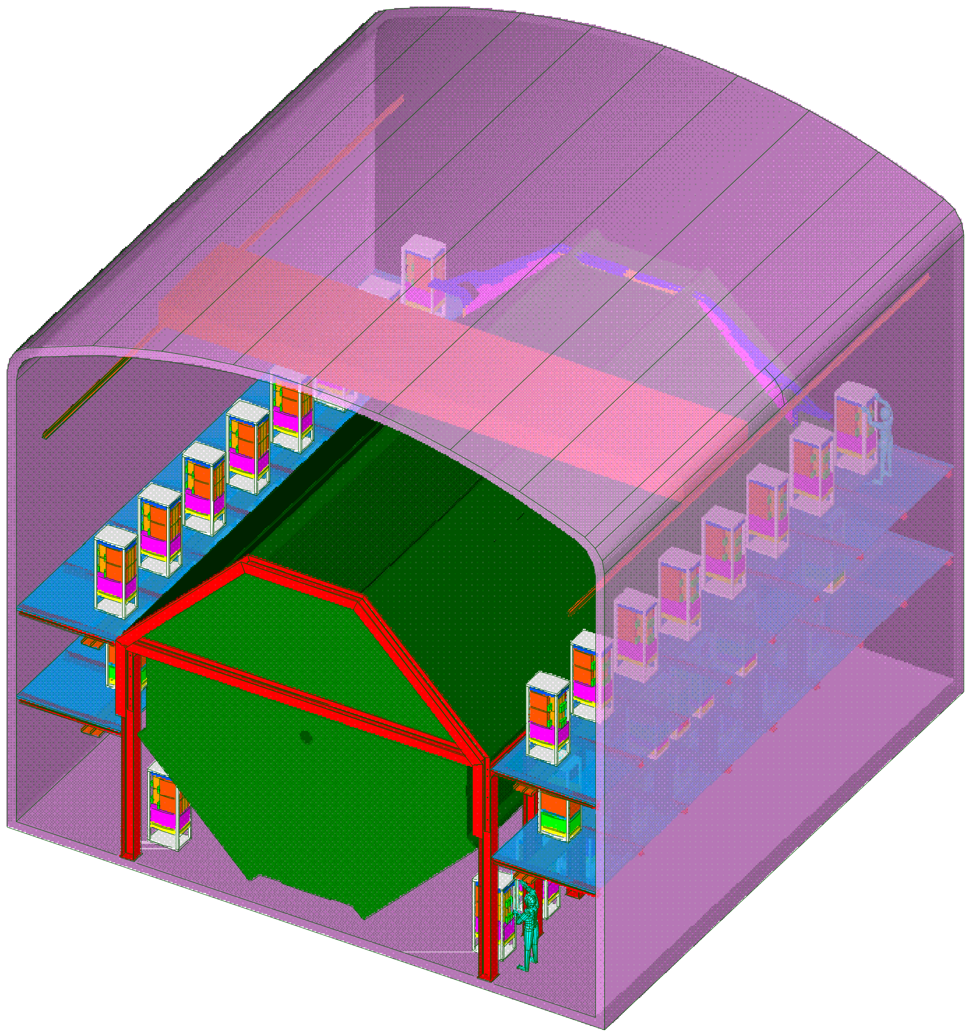

To Soudan
MINOS Near Detector
Decay
Enclosure
Target
Enclosure
Tevatron
Main
Injector

Neutrino Production



Milind Diwan, Brookhaven National Laboratory

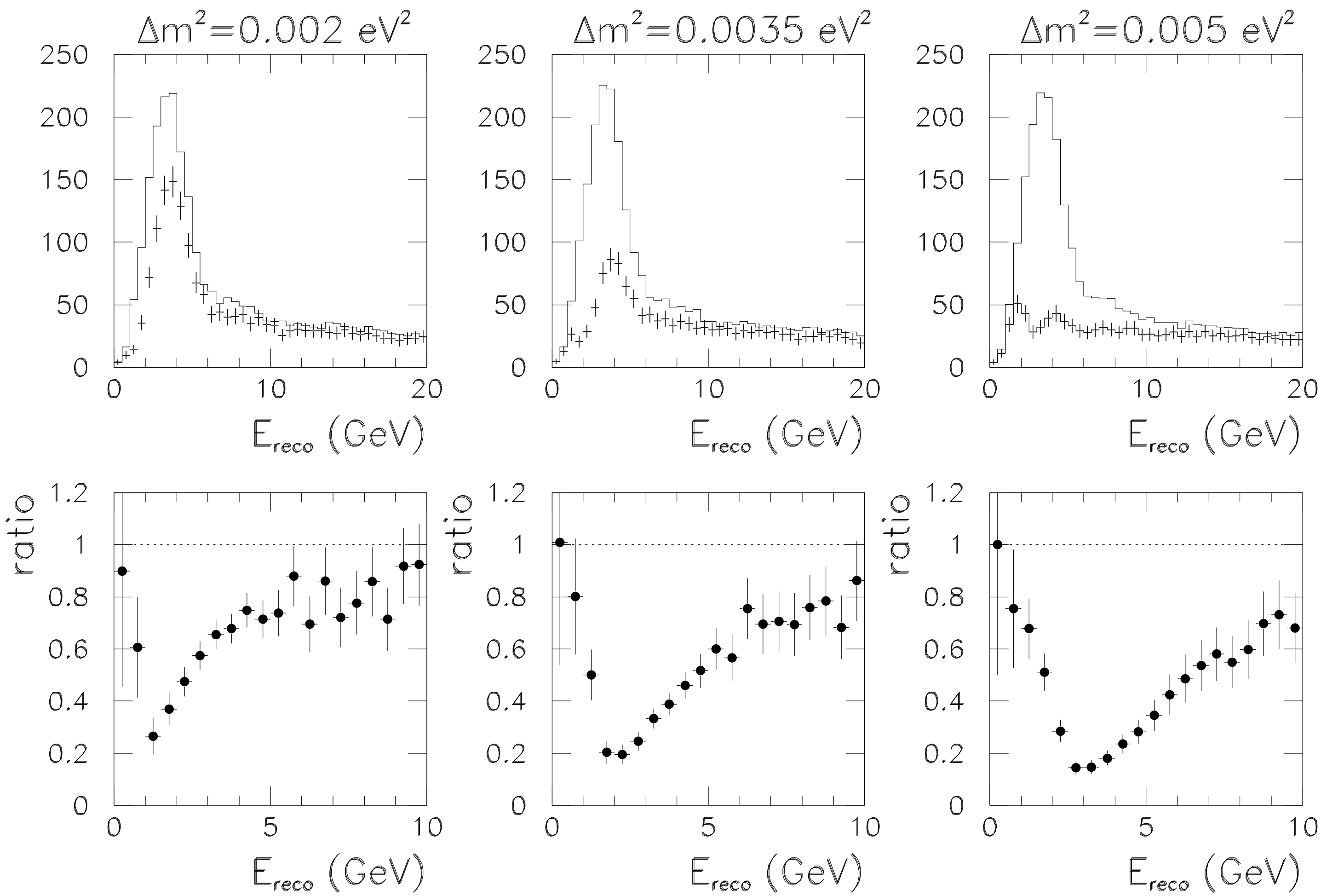
Far Detector



- 5.4kt (3.3kt fiducial)
- 486 steel planes (243/243)
- 484 scintillator planes (242/242)
- 192 scintillator strips/plane.
- 2 ended readout, 8x multiplexing

Expected Flux Distribution (ν_μ disappearance)

CC energy distributions – Ph2le, 10 kt.yr., $\sin^2(2\vartheta)=0.9$



Conclusion

- Over 100 years of science starting from beta decay.
- Neutrinos are finally beginning to yield their secrets.
- Will one of your students work on sending an even more intense beam to a detector 3000 km away ?
- Will one of your students figure out how to detect the cold neutrinos all around us: 300 per cm^3 ?